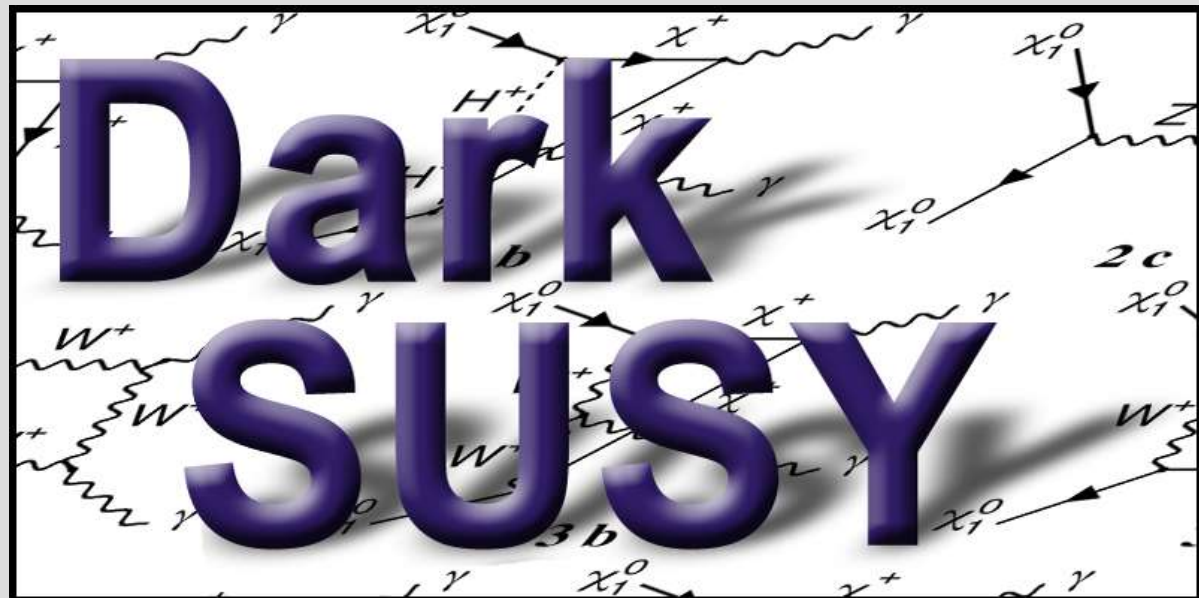


# Dark Matter in Minimal Supergravity

Markov Chain Monte Carlo  
Direct Detection  
Muon  $g-2$



Stanford  
Linear  
Accelerator  
Center



# Supersymmetry in One Slide

- SUSY adds “fermionic” dimensions to spacetime
- Particles get partners with spin different by  $\frac{1}{2}\hbar$ 
  - matter fermions → scalars
  - gauge, Higgs bosons → spin  $\frac{1}{2}$
- Numerous motivations
  - get fermions in string theory
  - relate bosons and fermions
  - gauge coupling unification
  - hierarchy problem
- Dark matter comes for free
  - R-parity imposed to stabilize proton – LSP is stable
- LSP is often gaugino/Higgsino
- SUSY is broken: mSUGRA
  - simple – 4 params. + 1 sign
  - scalar mass  $m_0$
  - gaugino mass  $m_{1/2}$
  - trilinear coupling  $A_0$
  - Higgs VEV ratio  $\tan\beta$
  - sign of Higgsino mass  $\text{sgn}(\mu)$
  - top mass  $m_t = 178.0 \pm 4.3 \text{ GeV}$
- RGEs from weak ↔ GUT scales
  - ISAJET package
  - gauge coupling unification
  - electroweak symmetry breaking
  - superpartner masses / mixings
    - is LSP a neutralino?
  - Higgs sector – 5 physical states

# Constraints and Observables for SUSY Models

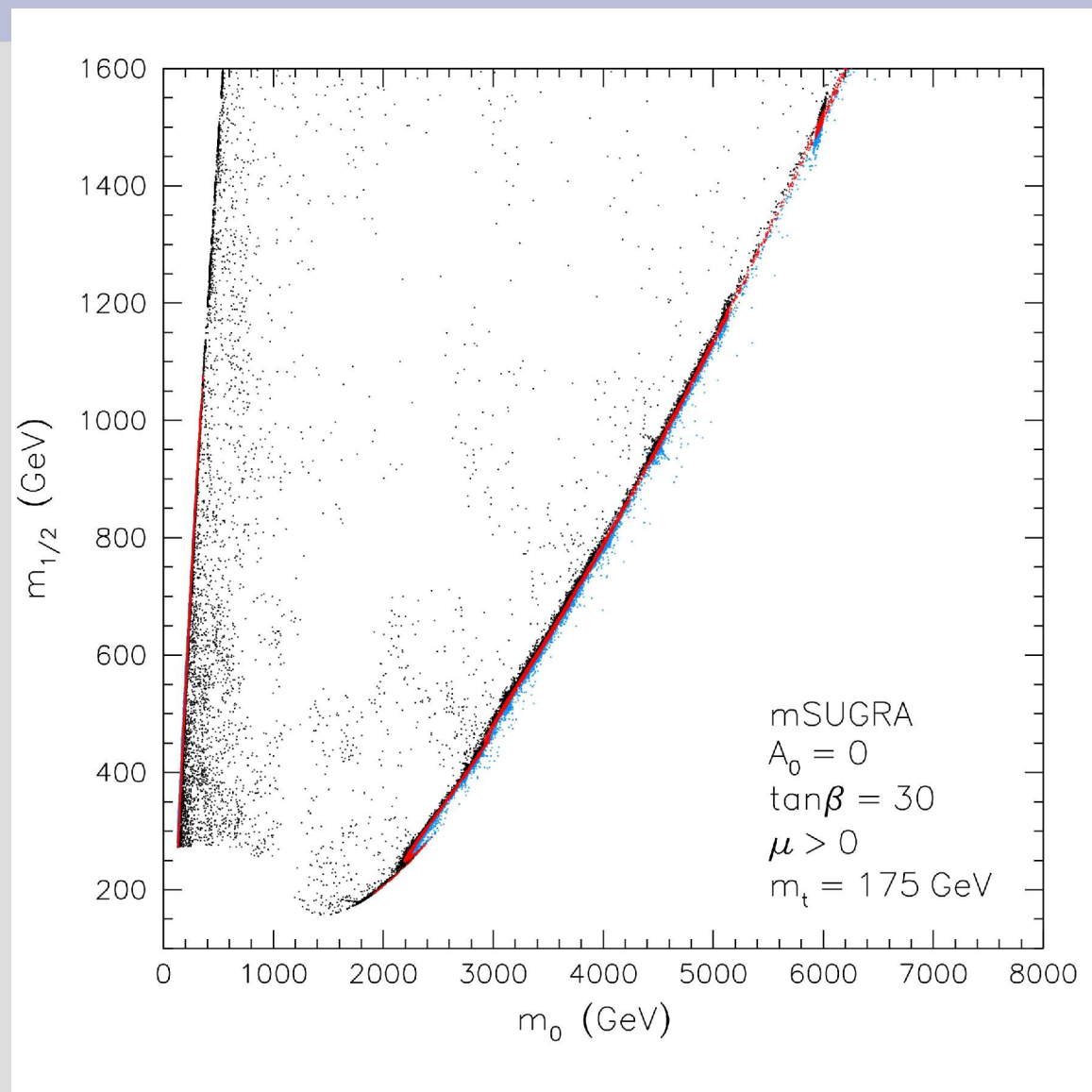
- **Accelerator constraints**
  - **Higgs mass**
  - **Sparticle masses**
    - chargino most important
    - LSP is neutralino
  - **$b \rightarrow s\gamma$  branching ratio**
  - **muon  $g-2$** 
    - situation still in flux
- **Cosmological constraint**
  - **relic density measured by WMAP**
  - **account for baryons, neutrinos?**
  - **95% confidence**  $0.087 < \Omega_{\text{cdm}} h^2 < 0.129$
- **DarkSUSY used to calculate relic density, astrophysical observables**
- **Direct detection: scattering cross-section on nuclei**
- **Neutrino telescopes: annihilations in Sun, Earth**
- **Indirect signatures of halo annihilations: antiprotons, positrons, antideuterons, gamma rays, synchrotron**
- **Low relic densities difficult to achieve in mSUGRA**
  - **sfermion (stau) coannihilations**
  - **chargino coannihilations**
  - **resonances (CP odd Higgs)**
- **These are all “special” regions**

# Efficient Scanning of Parameter Space

- Grid search is unacceptable for a 4D parameter space – 1% of models pass WMAP constraint
- Use relic density to guide the search of parameter space
- “Likelihood function” from WMAP – central value and error
  - **assume log-normal**
- Metropolis algorithm for Markov Chain Monte Carlo
  - **start at point  $P(i)$ , likelihood  $L(i)$**
  - **choose  $P$ , likelihood  $L$**
  - **$L > L(i)$ ,  $P(i+1) = P$**
  - **$L < L(i)$ ,  $P(i+1) = P$ , prob.  $L/L(i)$**
  - **otherwise  $P(i+1) = P(i)$**
- Construct many chains to map out acceptable region: points chosen from “true” posterior distribution if chain is converged
- Proposal step is crucial
  - **stepsize: ideal  $P(\text{accept})=0.2338$** 
    - adaptively adjust to match this
  - **step direction – degeneracies**
    - 4 parameters, one constraint = exact degeneracies
    - use gradient once likelihood is acceptable – step should be mostly perpendicular
- Efficiency is 25%
  - **far superior to grid search**
- Scan freely in 4 parameters
  - **not the usual 2D slices!**

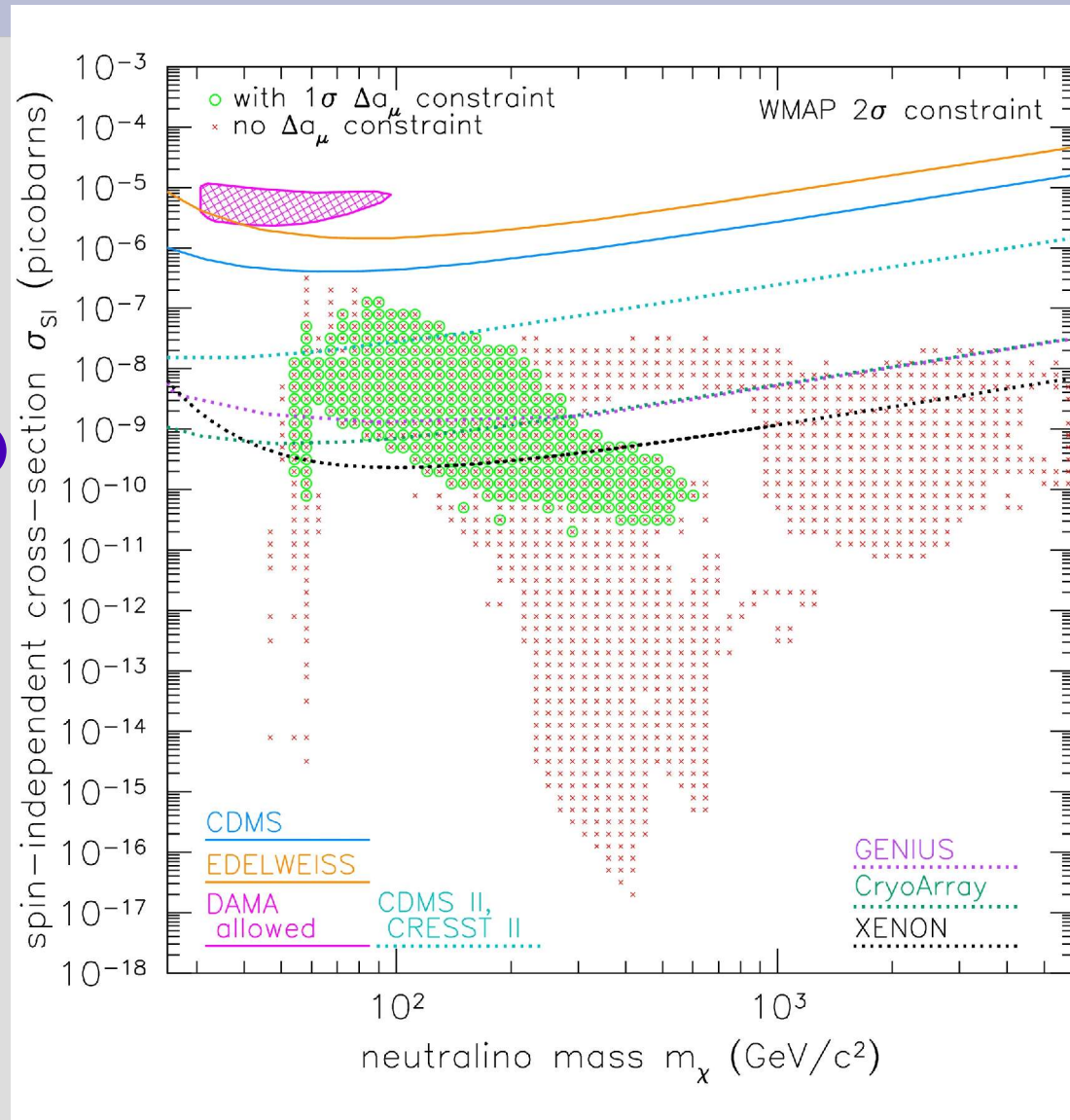
# A Two Parameter Illustration

- Fix  $A_0$ ,  $\tan\beta$ ,  $\mu > 0$
- Fix  $m_{\text{top}} = 175$  GeV
- MCMC scan in  $m_0$ ,  $m_{1/2}$
- Known regions found
  - **focus point (chargino coannihilations)**
  - **stau coannihilations**
- Efficiency is obvious from the figure: few points in unacceptable regions
- Focus point extends to 10 TeV neutralinos at least!
- Resonances appear at larger  $\tan\beta$



# Direct Detection

- 2.4 million models scanned, 500k pass 2 sigma WMAP
- Highlight g-2 within 1 sigma
  - **negative mu ruled out**
- Current experimental bounds (solid) and proposals (dashed)
- Higher cross sections possible in general models
- Very small cross sections possible, but mostly  $\mu < 0$
- These experiments have the potential to compete with LHC



# With WMAP

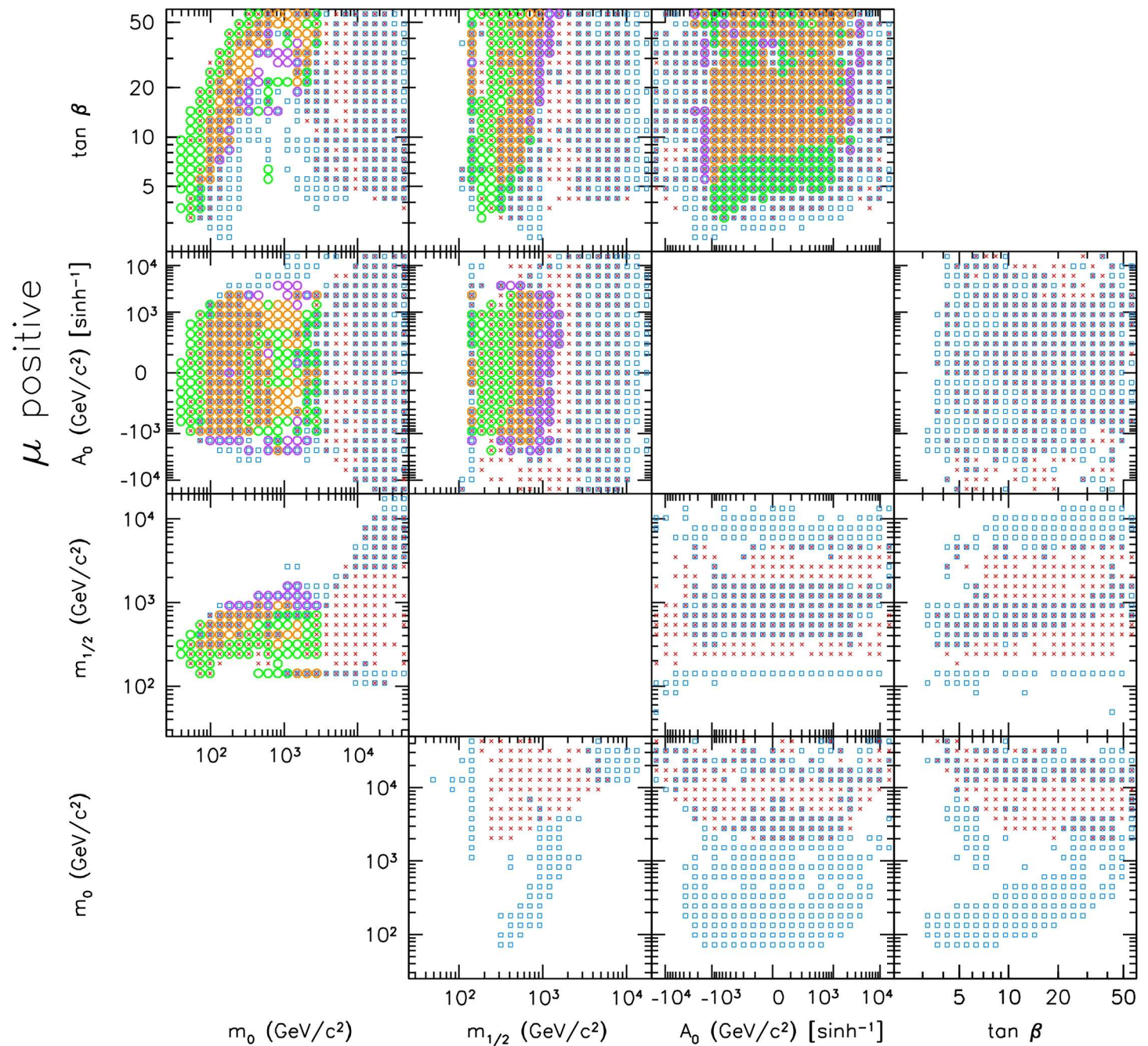
Green: good g-2  
detectable by XENON

Orange: good g-2  
some detectable

Purple: good g-2  
none detectable

Red: bad g-2  
detectable by XENON

Blue: bad g-2  
undetectable



$$0.087 \leq \Omega_\chi h^2 \leq 0.129$$

$\mu$  negative

# Without WMAP

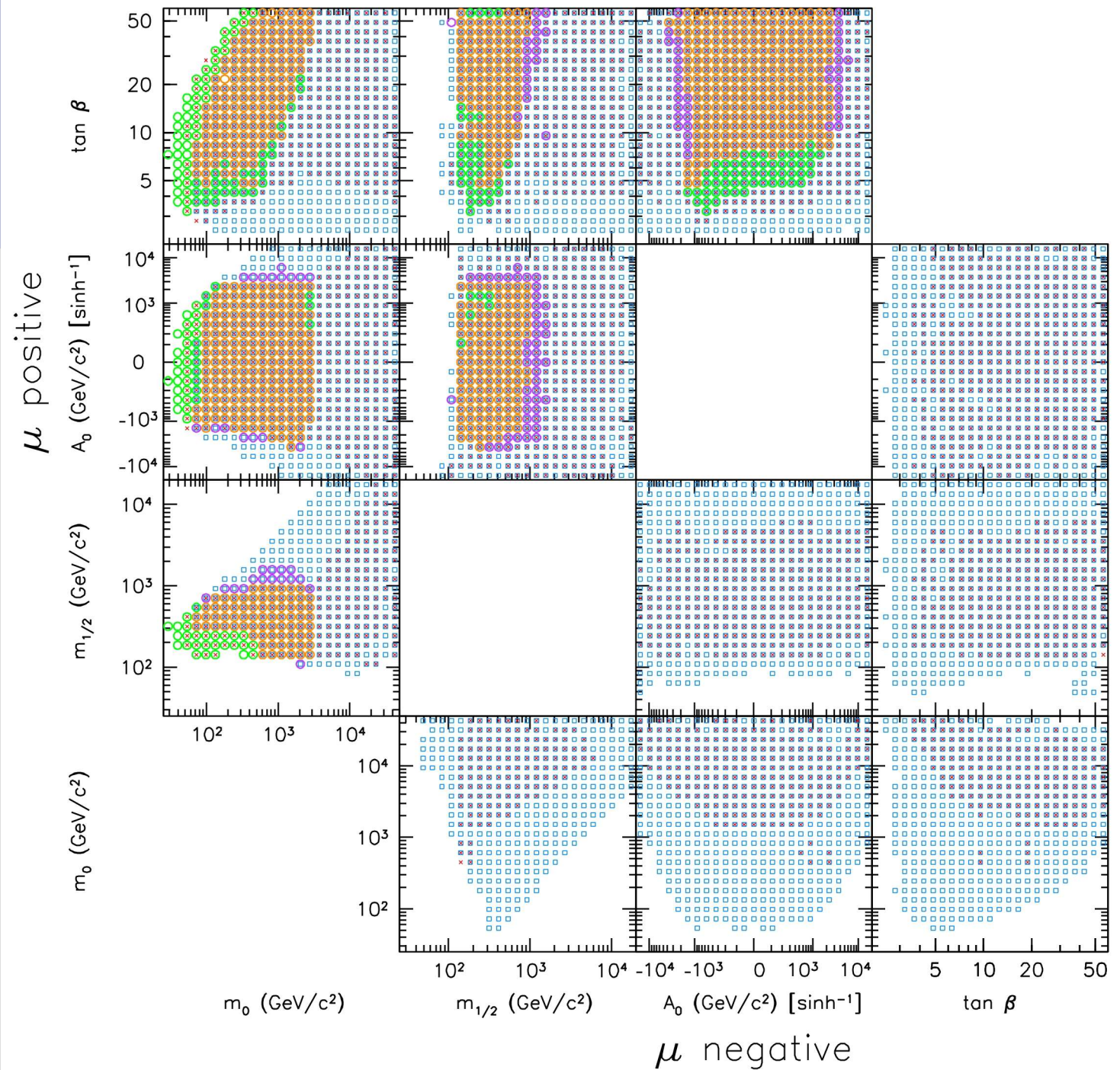
Green: good g-2  
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Orange: good g-2  
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Purple: good g-2  
none detectable

Red: bad g-2  
detectable by XENON

Blue: bad g-2  
undetectable



# Discussion

- **Assigning statistical meaning to density of points is dangerous, but we can say that the “special” regions are strongly favored by the WMAP result**
- **Is there a model framework with more natural DM?**
- **Break the various universalities: gaugino, sfermion, Higgs masses at the GUT scale**
- **In progress...**